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DUST STORMS ACCORDING TO DATA OF SPACE RESEARCH

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16. Abstract

Based upon space imagery, the main regions of the dust storm in the arid and sub-arid zones and the transfer paths of the dust materials are considered. Relationship between the dust storms and synoptic character and composition of the underlying surfaces is analyzed. On the example of the dust storm on the Mediterranean coast of Africa, the feasibility of studying the dynamics of these phenomena from space imagery is shown. The possibilities are considered of using the method of microphotometry of TV pictures for the estimation of the structure of dust storms. The main directions of the study of dust storms and flows using space imagery are indicated.

The booklet is intended for a wide circle of specialists in meteorology, atmospheric physics and geography.

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TABLE OF CONTENTS

ANNOTATIONS

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FOREWORD

More and more attention has been devoted recently to the problem of studying atmospheric contaminations, both natural and artificial. The study of such large-scale contaminations as dust storms, which are typical of arid and sub-arid regions, is of particular interest. In these areas, conditions are created that are favorable for the appearance of such phenomena as: extreme dryness and fragmentation of the surface layer of soil, low atmospheric humidity and strong winds. The turbulent whirlwinds that are formed raise dust material (small particles of the surface layer of soil), which is then caught up by wind currents and carried various distances. When the wind grows stronger, the amount of dust raised into the air increases and visibility worsens. Different wind speeds, depending on the structure of the surface layer of the soil, are required in order to raise and carry the dust. Thus, wind speeds of 10 - 12 meters per second are sufficient for the appearance of dust storms in the Volga region, for example, where the surface layer consists of very small and light particles of sandy loam soil. Sandstorms, for which high wind speeds (20 - 25 meters per second) are necessary, often appear in the deserts of Africa and Arabia. /3*

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The dimensions of dust storms vary from hundreds of square meters to hundreds and thousands of square kilometers.

Medium-scale and large-scale storms, i.e., those that can be seen from space, are divided by synoptic meteorologists into two basic types, in accordance with the nature of their origin.

The first type includes dust storms that originate during the passage of a cold front, and the second includes storms that originate in a so-called storm zone, which forms when two barometric pressure formations of opposite charge meet, and one of them increases sharply in intensity.

The dynamics and structure of these storms are different. Cold front storms pass through a number of stages in their development — from the formation of the storm center near ground level to the appearance of a dust cloud at high altitudes. The cloud is the result of the dust particles being carried upwards by powerful vertical currents in the area of the storm front (the place where cold and warm air masses meet), and of this dust being drawn into high-altitude atmospheric circulation (at altitudes of up to 3 - 5 km). The storm front moves as the barometric pressure formation moves.

The second type of storm is stationary in nature and encompasses /4
primarily the layer of air near the Earth (up to 1.5 - 2 km). The dust is carried in the form of dust currents that move in the same direction as the wind current.

Dust storms have been studied for a long time, since they do great harm to the economy. Both in the U.S.S.R. and abroad, a whole series of works have been devoted to studying the nature of dust storms, their frequency and the possibilities for predicting them [1 - 6]. However, because of the scattered nature of the observations by different researchers and the sparse network of meteorological stations on whose material they have relied in their works, it has not been possible to do a complete study of the laws governing the spread of dust storms, to estimate their scale and the routes along which the dust material is carried, or to determine their structure. With the development of space ecology [7], a new scientific trend in the study of the environment, great opportunities have opened up for the study of dust storms as well. Through the use of television (TV) pictures transmitted from meteorological artificial Earth satellites (AES), as well as through the use of photographs taken from manned spacecraft (MS) and automatic interplanetary stations (AIS), it has been found that many large scale and medium scale dust storms are easily visible from space and can be studied.

Dust storms and ~~sandstorms have been discovered~~ in the global space pictures received from the AIS Zond-5 and Zond-7 over Africa and over the Arabian Peninsula [8, 9, 10]. Dust storms have been recorded over the coastal region of Iran by the MS Gemini-6 [11]. Using TV pictures from the meteorological satellite ESSA-5, American specialists have succeeded in tracing a dust storm over the Atlantic Ocean off the coast of West Africa [12].

Soviet specialists have also recorded dust storms in this region, using TV pictures received from the American meteorological satellite ESSA-8. Measurements of the aerosol concentration were made on Earth at the same time that the pictures of the dust clouds were received [13, 14].

A successful study has been done of the structure of dust currents in the vicinity of Mesopotamia, with the aid of a microphotometric analysis of a TV picture of these currents received from the U.S. meteorological AES ITOS-1 at the meteorological satellite picture receiving station of the A. A. Zhdanov Leningrad State University [15].

The list of works devoted to the study of dust storms by means of space pictures that has been presented indicates how few such works there are. Moreover, these works elucidate only individual aspects of the phenomenon under consideration. Therefore, the authors have made an attempt to present a broader treatment of the various aspects of the problem of studying dust storms from outer space. For this purpose, an analysis has been done of space pictures received in various regions, the connection between dust storms and the underlying surface has been examined, and the structure of these phenomena has been studied.

1. THE PRINCIPAL REGIONS OF DUST STORMS ACCORDING TO OBSERVATIONS FROM SPACE

Analysis of the data concerning dust storms obtained from space pictures of a number of arid and semi-arid regions makes it possible to single out five regions. These regions are similar with respect to the nature of the formation, the structure, and the specific properties of the phenomenon, and their special features will be examined below. In the case of the first three regions, we shall describe storms connected with a cold front, and in the case of the last two — storms that originate in storm zones. /5

1.1. Central and West Africa. As may be seen from the fragment of the global space photograph (Figure 1), extremely long-distance dust currents recorded in the southern Sahara are developed over an enormous area — in a band that is about 2500 km long and about 600 km wide (from the Senegal River to Lake Chad). They appeared as a result of a formation in this area of an enormous air current moving from the west-southwest to the east-northeast. The dust was raised over the sandy deserts of Mauritania and Niger, which is easily visible from the bright tone of the picture, and from the manner in which the dust conceals the underlying surface (Figure 1, in which this region is indicated by means of the dust storm symbol S). The dust-storms are most clearly visible over dark-colored underlying surfaces with a low albedo value, in particular over the Adrar des Iforas Plateau, where the streams of the dust storm are easily visible (see also [10]).

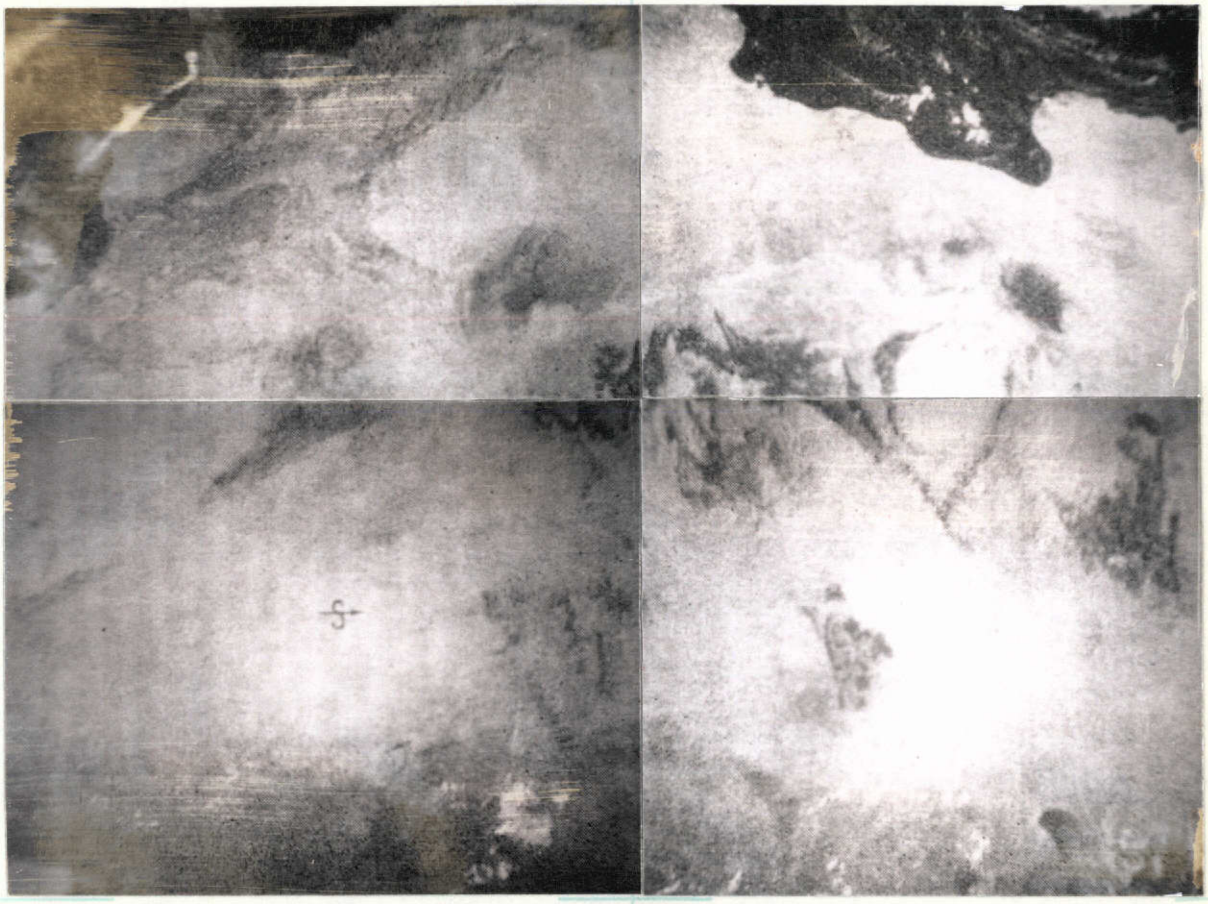

Figure 1. Dust storms in the Southern Sahara. Picture from the Soviet AIS Zond-5, September 9, 1968

An extremely long distance movement of dust from the western regions of the Sahara on June 7, 1967 was discovered in TV pictures received from the meteorological satellite ESSA-5 [12]. The dust cloud spread over the Atlantic Ocean off the northwest coast of Africa, over the so-called "Sea of Darkness" — a region in which dust carried from the western Sahara falls regularly. The dust cloud, which was discovered in the TV picture by American specialists, moved toward South America. After the appearance of the dust cloud off the coast of West Africa, dust that was obviously not of local origin was discovered some time later off the eastern coast of South America. Analysis of the TV pictures added substantially to the other data concerning the dust cloud (the meteorological situation, the composition and the location of the dust carried), and provided the most solid grounds for judgments about the possibility of extremely long distance movement of dust from one continent to another.

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It has been established that dust storms in these regions are caused by strong northeasterly trade winds (for which the local name is "harmattan"), which blow in the western and central Sahara in the summer as far as 20° N. lat., and in the winter as far as 6° N. lat. A large amount of dust material rises into the air where the harmattan meets the colder southwesterly monsoon. The masses of dust drawn into the atmospheric circulation are carried by the east-northeasterly wind currents over the cooler west-northwesterly monsoon current over the Atlantic. /7

1.2. The Mediterranean coastal region. In the television picture shown in Figure 2, we can easily see the area of the dust storm, which is brighter in tone than the surrounding desert; the southern boundary of the storm, which is called the "storm wall", is more sharply delineated. The cloud of raised dust material extends over the surface of the Mediterranean Sea. The storm originated during the passage of a cold front connected with a low pressure trough stretching toward North Africa from Western Europe, where there was a deep cyclone at that time. A detailed analysis of the origin and development of this storm will be presented in Section 3.

Storms of this type, which form on a cold front when cold air moves into North Africa with cyclones, are most typical of the African Mediterranean regions. This very dry and hot wind that carries clouds of sand and that is formed in front of a cold front of the so-called "khamsin depression" is called "gibleh" in Libya, "chili" in Morocco and Algeria, "chebili" in Tunisia, and "khamsin" in Egypt [16, 17].

1.3. East Africa. Dust storms are very frequent in the vicinity of the northeast Sudan.

The picture shown in Figure 3 is marked by a somewhat higher level of brightness; only in certain places can elements of the landscape, with high brightness contrast, be seen through the dust cloud. The boundaries of the dust cloud are very smooth. The northern boundary may be identified especially easily by the

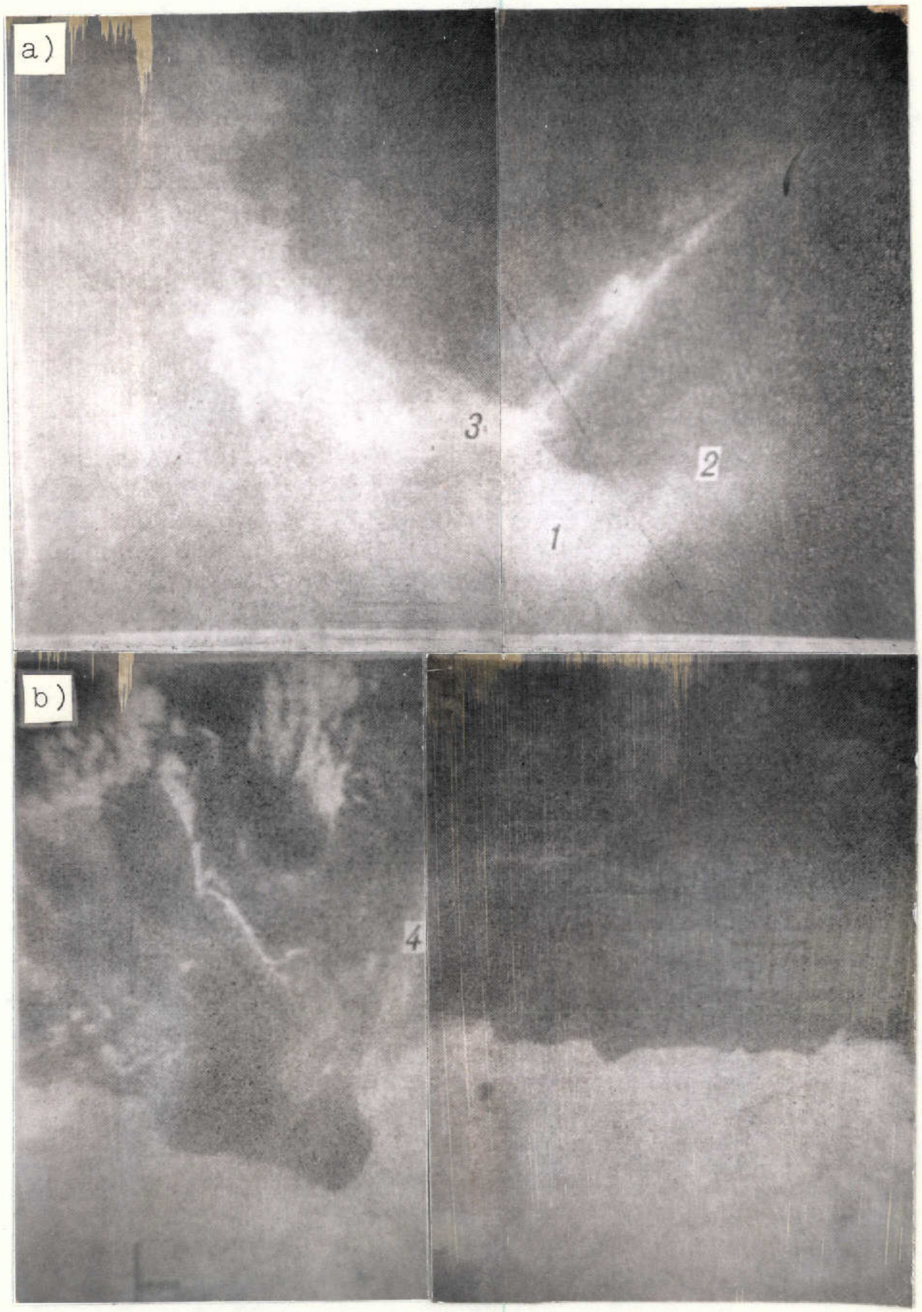

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Figure 2. Evolution of a dust storm originating over northern Africa:

a — the dust storm over northern Africa. Fragment of a TV picture from the American AES ITOS-1, taken on July 16, 1970; b — dust cloud over the Mediterranean Sea. Fragment of a TV picture from the American AES ESSA-8, taken on July 17, 1970.

discharge of the dust into the southern areas of the Red Sea. The picture of the dust cloud is brighter over the surface of the sea. The northern edge of this cloud is brighter, which is obviously connected with an increase in the concentration of the dust where the wind current slows down in the vicinity of the intratropical convergence zone. Its northern edge is easily visible over the land because of the curved "bar" of the storm. The weather station at Atbara, north of Khartoum and in the center of the storm, recorded a dust storm at that time in which the visibility was 800 meters. The winds in the center of the storm at wind-vane level were southwesterly, and had a speed of 10 - 15 meters per second. The storm originated because a cold northwesterly air current met a hot southwesterly monsoon current. Masses of dust were raised over an enormous area encompassing the region of the northeastern Sudan from the Nile River to the Red Sea. The dust, which was raised by powerful convection currents, was caught up by a high-altitude air current and carried across the mountains to the Red Sea coast, rising to an altitude of 3000 meters. At this altitude, a southwesterly current continued to carry the dust toward the Arabian Peninsula. /9

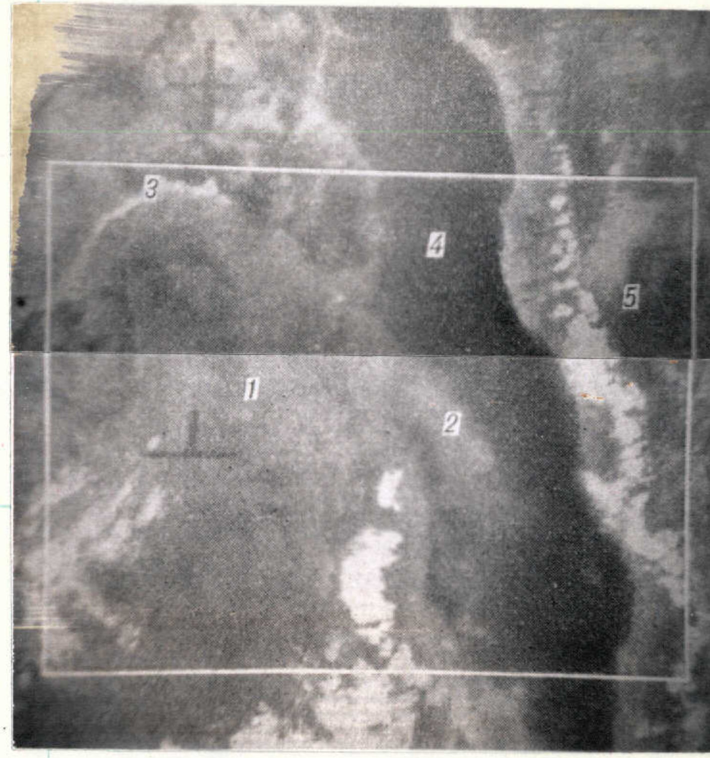

Figure 3. Dust storm in the area of the northeastern Sudan. Fragment of a TV picture from the American AES ITOS-1 taken on June 16, 1971:

1 — area of the storm; 2 — dust cloud over the Red Sea; 3 — squall cloud; 4 — the Red Sea; 5 — the Arabian peninsula

1.4. The Arabian Peninsula. Dust storms that form as a result of contact between two barometric pressure formations of opposite charge are most typical of this region. Such a storm was recorded at the meteorological satellite picture receiving station at L.S.U. (Leningrad State University) (Figure 4). In the fragment of the television picture, we can easily see a dust storm in the area of the Mesopotamian lowland, from 32° N. lat. down to and including the Persian Gulf. It is depicted in the form of several bands (four are visible) that are brighter than the surface of the valley. The continuation of these bands is most clearly visible against the dark background of the waters of the Persian Gulf.

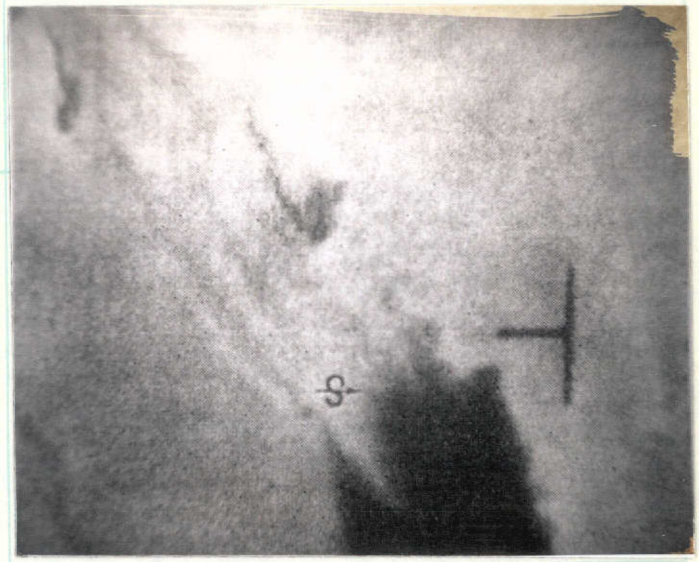

Figure 4. Dust storm over Mesopotamia. TV picture from the American AES ITOS-1, taken on July 17, 1970

The storm was caused by an increase of wind on the western periphery of a barometric pressure depression centered over southern Iran. Intensification of the ridge over the Mediterranean Sea caused an increase in the barometric pressure gradients there. In the area of the most powerful stream, weather stations recorded at that time a dust storm with a visibility of /10
1.5 km, and a wind speed at ground level of up to 20 - 25 meters per second. According to radiosonde data, the wind increased with altitude, reaching a maximum value (36 meters per second) at an altitude of 1.5 km. Then the wind speed began to fall off sharply. The humidity of the air in the area of the storm was about 15%. The vertical temperature gradients up to an altitude of 1.5 km had superadiabatic values (greater than 1° C). Obviously, the altitude of the dust layer was 1.5 - 2 km.

A similar dust storm was observed in this region on August 12, 1968 (Figure 5). In the TV picture (Figure 5a), it is visible in the form of three cone-shaped streams that are expanding as they move southward, and that are considerably brighter in tone than the surrounding surface. The individual streams of this storm, just as in Figure 4, begin in the very same areas, which are evidently the most

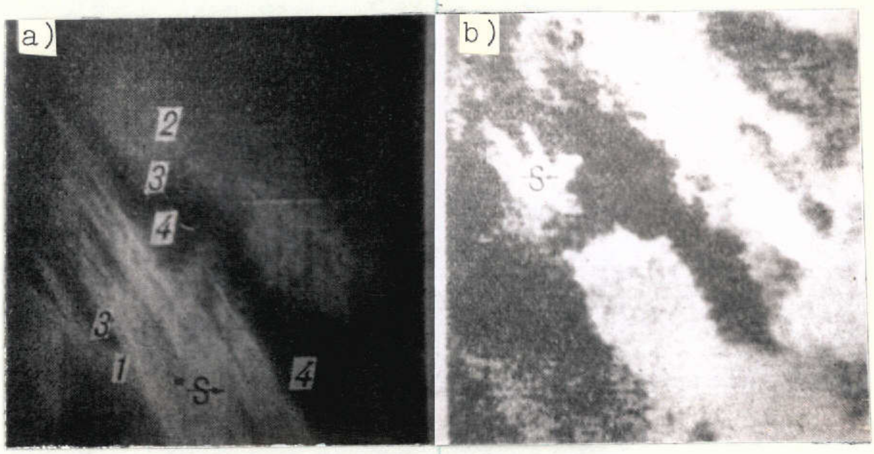

Figure 5. Television (a) and infrared (b) pictures of a dust storm in Mesopotamia from the Soviet AES Kosmos-226, taken on August 12, 1968:

1 — the sands of Er Rakhab; 3 — elevated watershed plain; 3 — valleys with thick plant cover; 4 — flat accumulative lowland plains

favorable for the formation of storms. In addition, the smaller-scale structure of the streams themselves is easily visible in Figure 5a. In the area in which they originate, the streams consist of smaller parallel streams that are 3 - 5 km in size, and that obviously correspond to the centers of the dust whirlwinds. The dust that is raised in the area of these centers is first carried in the form of individual streams for a distance of up to 100 km from the place where the streams originate to the place where they merge and form more powerful streams. These streams take the form of swirling and expanding bands, which is connected with the strong convection /11
in the layer of air nearest the Earth and the high pulsation of the wind speed and direction. The total length of the dust storm shown in Figure 5a is 500 km. The dust storm is also easily visible in

the infrared picture (Figure 5b), in which it is also depicted in the form of three streams, whose brightness is equal to that of the Persian Gulf and of the extremely swampy, wet, colder and lower part of the Mesopotamian lowland.

According to actinometric data, the radiation temperature in these areas was about 15 - 20° C. In point of fact, the actual surface temperature (corrected) was 15° C higher. The temperature values obtained made it possible, using high-altitude data concerning the course of the temperature, to determine the altitude of the dust layer (from 1 to 1.5 km).

The nature of picture recorded in Figure 5a divides the zone of dust turbidity into two different parts: the northern area, which is smaller in size and in which dust whirlwinds develop that correspond to the centers of the dust storm and that are not oriented in a plane, and the southern area, which is more extensive and in which dust streams develop that extend in the same direction as the prevailing winds.

The air current that picks up the dust material can carry it further south. Thus, in the fragment of the space color picture (Figure 6), bright bands connected with dust turbidity are visible in the southern part of the Persian Gulf, where the trade air current is slowing down because it is meeting a southwesterly monsoon current. The masses of dust picked up by the trade current are carried through an enormous corridor, bounded on the north by the mountains of the southern edge of Asia Minor and of Iraq, and on the south by the /12
plateaus and mountains of Saudi Arabia (Figure 7). The zone in which the trade current and the monsoon meet is depicted in the picture (Figure 6) in the form of a dark (red in the color photograph) band. Another current, originating in East Africa (the band that is brighter in tone), is connected with monsoon circulation. It is especially clearly visible in the southern part of the Red Sea. This band then moves into the northeastern part of Arabia, and becomes easily visible against the background of the surface of the Persian Gulf and the

Arabian Sea. There it divides into two parts. One goes around the elevation located at the northeastern extremity of the Arabian Peninsula from the north, and the other goes around from the south.

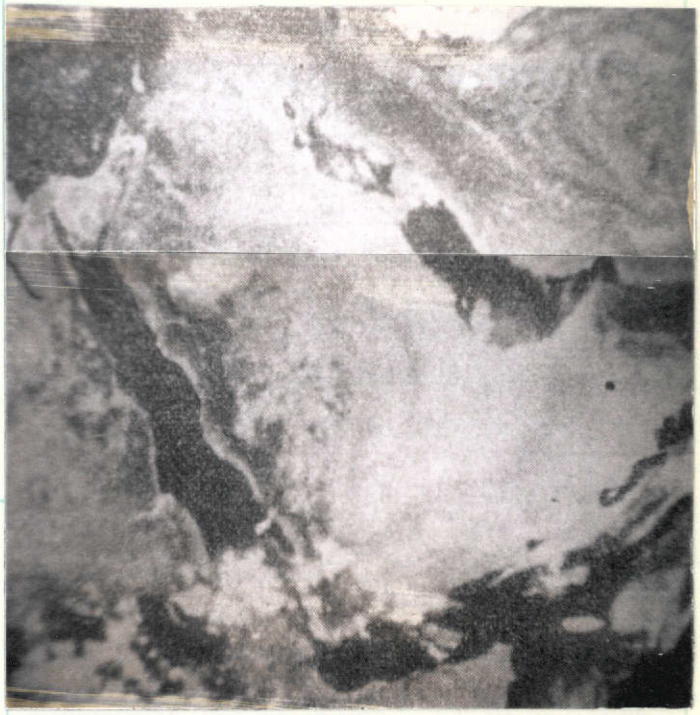

Figure 6. Dust currents over the Arabian Peninsula. Picture from the Soviet AIS Zond-7, taken on August 8, 1968

1.5. The Lower Volga and the North Caucasus. Storm zone formations are typical of these regions. A storm of this type was recorded in a TV picture of the lower reaches of the Volga River, taken on June 13, 1970 (Figure 8). The area of the storm to the west of the Volga River is marked by a brighter spot with blurred boundaries, which conceal the details of the surface. In certain places, this spot has a striated structure. The surface encompassed by the storm, which is centered in the area of the Kalmyk Steppes, extends from the Tsimlyanskaya Reservoir almost to the Caspian Sea itself.

The dust storm encompasses an area that is about 450 km long and about 250 km wide. This area is located in the dry-steppe zone, in which there are many flat and rolling elevations, broken up in places by a network of ravines and gullies, and many watershed plains with a widely developed cover of loessoid deposits that are poorly secured by vegetation. These deposits blow away easily, and serve as the source for the formation of dust storms. /13

Since the surface details throughout that part of the photograph covering the area west of the Volga cannot be seen very well, it is obvious that the turbidity of the atmosphere encompasses a considerably greater area. All the weather stations located in the area of the storm recorded a worsening of visibility to 7 km, and the stations located in the center of the storm recorded a worsening of visibility to 4 km. According to data from measurements at various altitudes, southeasterly and southerly winds were observed up to an altitude of 2 km, and the maximum wind speed at an altitude of 1.5 km reached 13 meters per second.

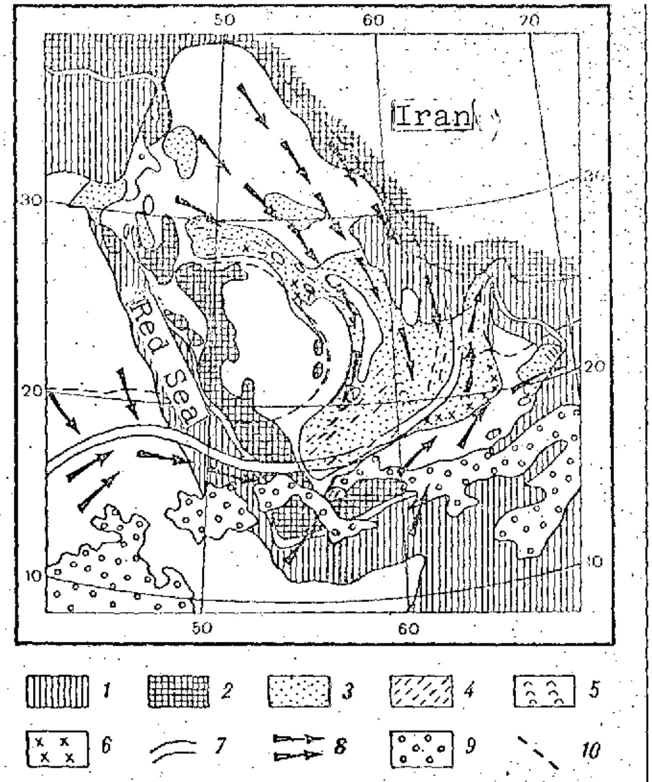

Figure 7. Map-diagram with dust currents over the Arabian Peninsula, from a space picture from the AIS Zond-7 (see Figure 6):

1 — water; 2 — mountains and plateaus with altitudes of 1.8 km; 3 — areas of the development of sand deflation; 4 — areas of the occurrence of seifs; 5 — barkhans; 6 — unoriented aeolian forms; 7 — intratropical convergence zone; 8 — direction of dust currents; 9 — cloudiness; 10 — boundary of the dust currents

/15

According to radiosonde data from the Volgograd weather station, superadiabatic temperature gradients were observed up to an altitude of 2 km, and above that level there was an isothermic layer. The southerly wind reached its maximum speed at an altitude of 1.8 km. Therefore, it may be assumed that the dust layer extended to an altitude of about 2 km, and was not observed at ground level.

Actinometric measurements at the Volgograd weather station revealed the existence of severe atmospheric turbidity at 6:30 p.m. Direct solar radiation decreased by half, as compared with the previous day, while diffused radiation increased. Since the northern

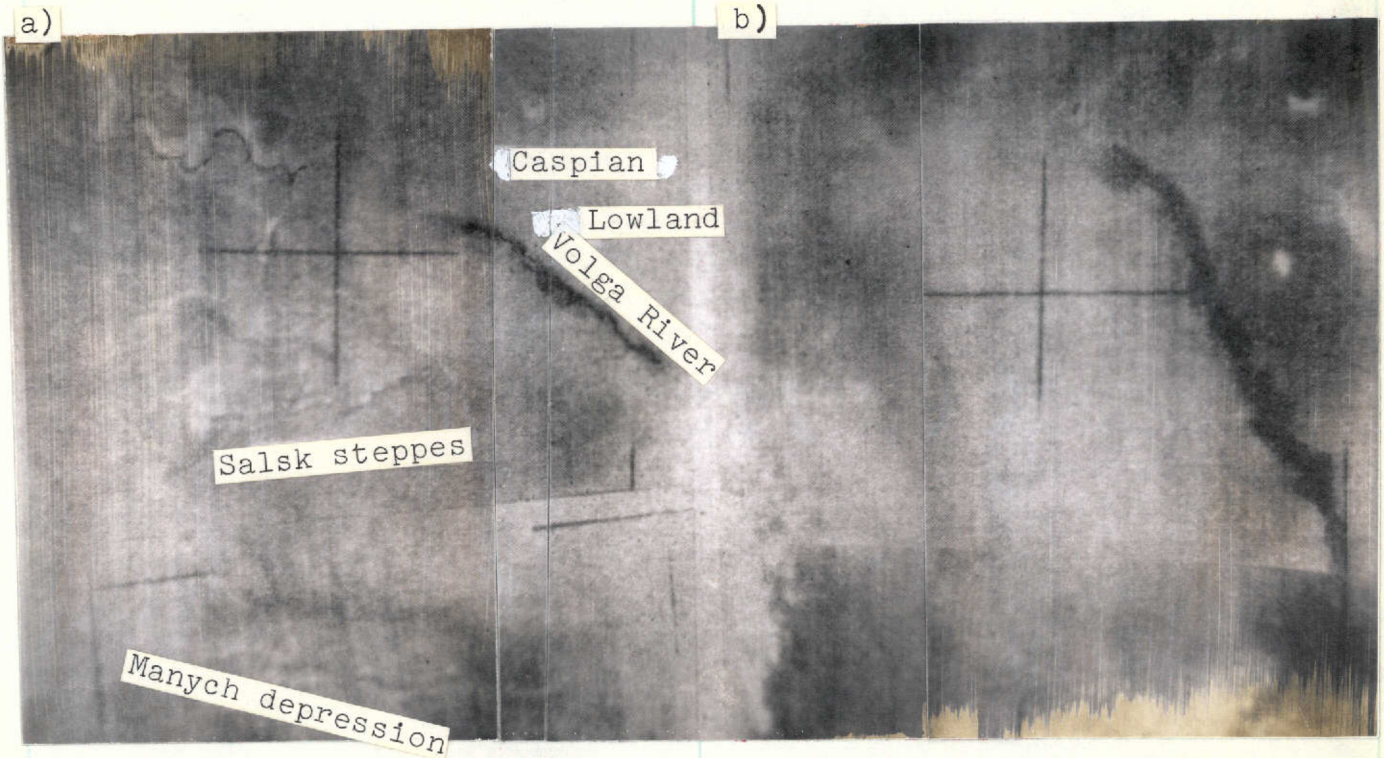

Figure 8. The Lower Volga Region without a storm at 7:00 a.m. on June 13, 1970 (a), and with a dust storm at 5:00 p.m. on June 13, 1970 (b). TV picture from the Soviet AES Meteor-4

boundary of the dust storm in the vicinity of the Tsimlyanskaya Reservoir, according to ground-level data, was located 130 km south of the boundary of the dust cloud recorded in the TV picture (Figure 8b), and according to radiosonde data the dust should not have risen higher than 2 km, it proved to be possible, using the Stokes formula, to calculate the size of the particles carried at a speed of 13 meters per second, and to establish that the dust cloud over the Tsimlyanskaya Reservoir must have consisted of particles no larger than 25 microns. The storm was caused by an increase in the barometric pressure gradients on the northwestern periphery of the higher pressure ridge that extended to the regions of the Volga River and Central Asia. The increase in the barometric pressure gradients was caused by the movement of a cyclone away into northern Europe, and the spread of the low pressure trough to the south of the cyclone.

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The analysis that has been presented of space pictures of dust storms in arid and sub-arid zones makes it possible to study more comprehensively the mechanism of their formation, and to determine the principal routes along which the dust material is carried.

Dust is constantly being carried out of West Africa by trade wind currents. From North Africa, cyclones draw the dust into their circulation and carry it great distances to Western Europe. From East Africa, the dust raised in the area of the disturbances arising on the tropical front and picked up by the monsoon current is carried across Arabia to the Arabian Sea. The Arabian Peninsula in turn is also an enormous "corridor", through which masses of dust material are carried by the northwesterly trade currents on the western periphery of the Iranian barometric pressure depression.

2. THE CONNECTION BETWEEN DUST STORMS AND THE DIFFERENT FORMS OF UNDERLYING SURFACE

<u>2.1. Large scale and medium scale forms of relief</u>. The direction in which the dust currents arising during dust storms move correlates to a considerable extent with the occurrence and nature of the large forms of relief (large scale relief) that are encountered /16 on the path of the wind currents. Space pictures, particularly extremely small scale pictures, that record an instantaneous picture of the movement of dust storms along the entire path of their spread make it possible to make a graphic assessment of this role of large scale relief. For example, analysis of global photographs of the Arabian Peninsula (see Figure 6) shows that the beginning of one of the two dust currents recorded in the photo is located over the eastern part of the Mediterranean Sea and Asia Minor. Its movement from that area in a broad band 300 km wide that goes southeastward over northern Arabia, Iraq, and southwestern Iran is easily visible. One notes a high degree of correspondence in the extent of the current and of the large forms of relief. The current moves over the lowest,

northern part of the Arabian Peninsula and over the plains of central and southern Arabia. This direction of the dust current is determined both by the direction of the winds and by the extent of the mountain ranges of Iran (Zagros), which bound it on the north and northeast, and of the elevations and plateaus of central Arabia, which bound it on the south and west. Through this natural corridor, as if in a wind tunnel, the current moves more than 2000 km, gradually deviating toward the west and flowing around the Tuwayq Mountains. Changing its direction toward the south and southwest, the current moves onward, hemmed in on the west by the Tuwayq Mountains and on the south and southeast by the Mahrat Mountains and by the Kathiri elevation. It should be noted that the elevations of central Arabia skirted by the current are considerably lower than the Zagros Mountains (correspondingly, 650 - 900 meters; infrequently, 1000 meters and 1500 - 4500 meters; on the average, about 3000 meters); in altitude they exceed by a maximum of 400 - 450 meters the plains adjacent to them, over which the current moves.

In the southern part of the Rub' al Khali Desert, the air corridor narrows, and then it passes through the narrow opening between the Kathiri elevations and through the Ar Rayyan region. It again widens in the Rub' al Khali Desert, and further south it encounters an orographic barrier in the form of the mountains of southwestern Saudi Arabia (whose watershed ridges exceed 3 km), which cut down the speed of the air current.

As is easily visible in the TV photographs, a similar influence on the movement of the dust currents is exerted by the numerous large monadnock elevations and stony plateaus that rise among the sandy and rock-clay plains of North Africa.

Medium size forms of relief (medium scale relief) exert a similar influence on the movement of the dust currents, although on a considerably smaller scale. This can be seen from the example of local space photographs of a dust storm in Arabia (Figure 9). The dust current connected with the storm, which originated at the bottom

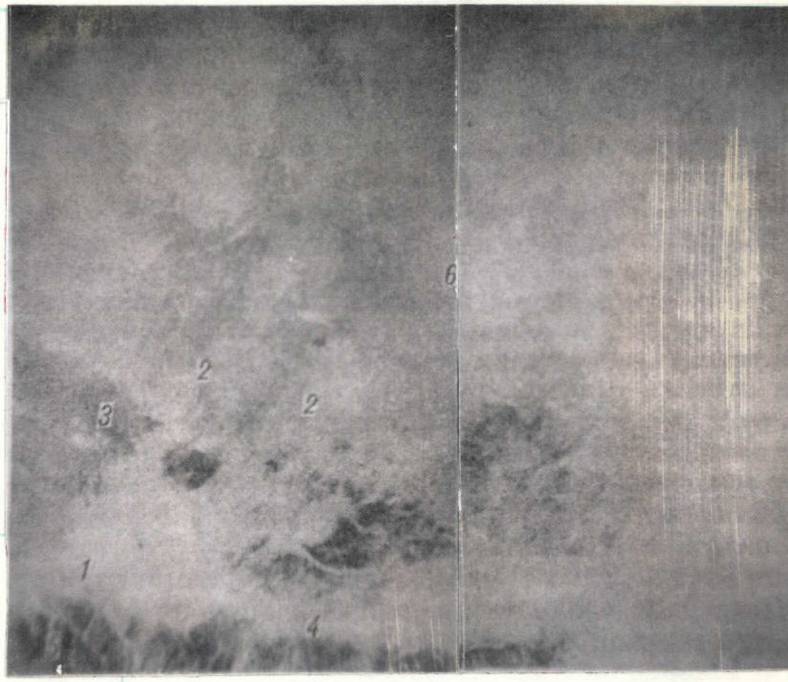

Figure 9. Dust storm over the deserts of northwestern Arabia. TV picture from the Soviet AES Soyuz-9, June, 1970:

1 — center of the dust storm over the bottom of a wadi containing salt marshes (Sabkhat Hazawza); 2 — largest streams of the dust current; 3 — low volcanic mountains; 4 — valley-type depression in the Jabal Amud Plateau; 5 — the intensively fragmented Ard es Suwwan Plateau; 6 — the flat Jabal Amud Plateau

of an intermontane depression, moves eastward through the wide "gates" in the wall of the mountain ranges that bound the basin. Moving out of the basin onto the plain, this current changes its direction somewhat because of the action of the wind, and shifts toward the north. The elevations (monad- /17 nocks) that are encountered on the path of the dust current divide it into separate streams, which is confirmed by its striation in the photographs.

<u>2.2 Aeolian forms of relief</u>. Traces of aeolian (wind) accumulation or diverse forms of aeolian relief are easily visible in space photographs of sufficiently high resolution. The largest aeolian forms, e.g., the enormous longitudinal dunes, may be distinguished in photographs with a resolution of several hundred meters, while identification of the crescent shape barkhans and small ridges is possible only in photographs with a resolution of several dozen meters. Analysis of space photographs, chiefly of photographs from MS, of various sandy deserts of the world that have been often very poorly studied has made it possible to acquire a considerably more precise knowledge of the configuration of the occurrence of aeolian forms. Comparative study of local photographs of various scales from MS and of whole fields of these forms, as well as of extremely

small scale global photographs of arid and semi-arid regions from AES or AIS that record large dust storms and the dust currents connected with them, has made it possible to discover certain laws governing the formation of aeolian relief, whose configuration and occurrence can serve as an indicator of the movement of dust-and-sand material. Let us examine an example, in order to see the advantage of such combined use of local and global space photographs for studying the interconnection between aeolian relief and dust currents. The zone of the movement of the dust currents recorded in a global space photograph from the AIS Zond-7 (see Figure 6) corresponds to the areas of development of such large sand masses as the Great Nafud, the Little Nafud (Dekhna) and the Rub' al Khali Deserts (the last being the largest of them). Various types of aeolian relief, with the predominant type being the ridge relief of the seifs (longitudinal dunes), are developed in these deserts in the zone of the movement of the currents; the spread of the seifs to the individual regions of Arabia has been clarified to a considerable extent through interpretation of local space photographs from MS [18, 19]. The space photographs have shown that the seifs in the Ramlat Sab'atayn Desert (the southern part of the Rub' al Khali) vary in length from 3 to 60 km, and in width from 1.5 to 4.5 km (with a height up to 60 meters or more). Comparison of the spread of the seifs* and of the dust wind currents identified in the photograph from the AIS Zond-7 reveals a high degree of correspondence in their orientation along the entire path of the currents (see Figure 7). /18

The seifs of the Great Nafud Desert (in the Ad Dahna region), which are oriented in a northwest to southeast direction, give way to the seifs of the Little Nafud Desert (Dekhna), whose direction gradually changes near the border with the Rub'aal Kahli Desert. In the Rub' al Khali Desert, the seifs are oriented in a north-northeast to south-southwest direction (Al Mikhrad), and then in a

*In order to estimate the orientation of the seifs, available maps [20, 21, 22], which on the whole were rather schematic, were used; in the case of certain regions, space photographs, which provide more precise information, were used.

northeast to a southwest direction (Al Kaamiyat, Ramlat Yam, Ramlat Sab'atayn, etc.). The last traces of aeolian activity on the path of the air current are observed in the Ramlat Sab'atayn Desert. In the space photographs from MS, one may easily see how the seifs come right up to the mountain ranges that bound the desert on the south and southwest [19]. The mountains of Yemen, whose altitude goes up to 2.0 - 3.5 km, serve as an important orographic barrier for ground level winds in this direction, which die down at the foot of these mountains (the spurs of the mountains are about 500 meters higher than the adjacent desert, while the summits are approximately 1.5 - 2.5 km higher). ~~Because of the drop in the wind~~ speed, only some of the seifs, as they rise on the sloping plain, go almost right up to the mountains.

Each seif constitutes a particle of a single gigantic system of seifs, which are formed as a result of the constant action of the winds blowing in stable directions. The corridor through which the air current moves is curved because of the orientation of the large forms of the relief of Arabia and Iran; it is determined by the deflection of the air currents, which leads, during periods in which strong winds (simoons) are prevailing, to the formation of powerful dust currents in the form of gigantic whirlwinds, of which two are recorded in the photo (see Figure 6). /19

The origin of other types of aeolian forms that are encountered in the zone of movement of the air currents, but are not oriented in the same direction as this movement, is primarily connected with a decrease in the speed of the current, which is caused by the presence of orographic boundaries (for example, the Aja Mountains which bound the deserts of the Great Nafud on the southeast), or with the location of the current in a boundary zone (for example, in the vicinity of Al Jiwa oasis in the eastern part of the Rub' al Khali). Aeolian forms of other types and with other orientations sometimes occur in these zones, in which the effect of the air current is decreased and in which winds blow in other directions periodically (for example, in the Ramlat ibn Swaidan region and the eastern part of the Rub' al Khali).

Thus, on the whole, the occurrence of most of the aeolian forms in the Arabian desert is connected to one extent or another with the constant air current that is observed over its entire area.

Analysis of extremely small scale space photographs has made it possible to discover the most important, previously unknown laws governing the distribution of aeolian ridge forms, and to establish their connection with present day air currents. Interpretation of larger scale space photographs received from MS* has made it possible to fill out the details of the general picture of the occurrence of the aeolian forms that reflect the nature of the movement of the dust currents.

2.3. Soils of the underlying surface. Space pictures record in a rather detailed manner the structure of the landscape; interpretation of the features of the landscape makes it possible to judge the nature of the soils of the underlying surface. Analysis of smaller scale TV pictures provides relatively more detailed information about the landscape and, consequently, about the nature of the soils [24]. Considerably more detailed information may be obtained from the original photographs from MS that show in a differentiated manner the surface deposits, which vary with respect to their genesis, lithologic composition, moisture content and the degree to which they are secured by vegetation [25]. Space pictures of any scale that depict a dust storm clearly record the area in which it originates. This opens up great opportunities for localizing the centers of development of dust storms, and for discovering the features of the structure of the landscape, including the soils, that have an effect on their origin.

A center of the origin of a dust storm is clearly visible in the space photograph shown in Figure 9. The dust current takes the form of a whitish, typically extended spot that conceals certain

*See, for example, [23], Chapter 3, Section 4 for data with respect to analysis of space photographs of aeolian forms in the sand mass of Borig Del.

elements of the structure of the landscape. The erosion forms, in the form of small bedrock monadnocks that may be seen in the photograph partially outside the zone of the dust current, are also /20 shown on topographical maps of this region. The dust current begins in a broad valley — on the flat dry bottom that stretches along the foot of the Ard es Suwwan Plateau — that is filled with clay proluvial (from intermittent watercourses) deposits. Salt marshes are developed in the northern parts of the depression. Masses of the salt, as well as clay particles, that compose the dry bottom of the valley, have been set into motion by a local wind current that has arisen. Such local salt dust storms are extremely typical of an arid zone in which salt marshes are widespread.

In order to study the structure of dust and sand currents, it is necessary to do an analysis of the composition of the friable deposits and the nature of the soil cover of the regions over which they are formed. As an example, we shall examine a regional TV picture of a dust storm that developed over the territory of Mesopotamia (see Figure 4).

In the picture, the dust storm becomes visible to the southeast of Lakes Bahr al Milh and Mileh Thartar, where the wind current increases sharply and picks up large numbers of dust particles from the loessoid surface deposits.

In the lowland of the Tigris and Euphrates Rivers, in contrast to the adjacent deserts of northern Arabia, alluvial deposits that are friable, very fine, and primarily composed of clay are widespread. The dried-up bottoms of the intermittent lakes also yield abundant dust material, but in smaller amounts.

The brightest stream of the dust storm begins in the Az Rakhab zone of unsecured sand, and passes over a comparatively narrow (20–25 km) band that extends from the northwest to the southeast in the direction in which the dust is moving. This zone consists of separate masses of dust sand, with a total length of more than 200 km. The origin of the most powerful and clearly visible (in the TV picture) stream of the storm is connected with the scattering of the unsecured sand. The air streams over the central and northern parts of the lowland that are smaller in size contain considerably less suspended material, since they pass over lakes, swamps, kevirs (wet salt marshes) and relatively better-secured watershed areas.

What has been set forth makes it possible to conclude that space pictures that record dust wind formation and the landscapes over which they develop make it possible to obtain important indirect data concerning the composition of the deposits that are carried by the wind, which may be fed by sand, salt, loessoid loam, etc. According to the data from analysis of the pictures from MS, the most important sources of the dustiness of the atmosphere are the sandy deserts of Africa and Arabia; seifs whose orientation reflects the direction of the paths of the dust currents are widespread in these deserts. Color photogrpahs from MS have revealed significant variations in color among the underlying surfaces in the regions in which dust storms originate. These variations are engendered by the specific nature of the composition and erosion of the surface deposits. In particular, it was precisely by means of photographs from MS /21 that it was discovered that underlying surfaces in whose coloring reddish hues predominate are strikingly widespread in the deserts of Africa. In this connection, opportunities have opened up for a comparative study of the correlation between the color variations among underlying surfaces (on the basis of data from analysis of color photographs of the regions in which dust storms originate) and colored dust precipitation in the regions in which it falls (on the basis of data from ground-level studies).

3. THE DYNAMICS AND STRUCTURE OF DUST STORMS

3.1. The evolution of the movement of dust storms. Television pictures received from the Soviet Meteor meteorological satellites, as well as from the American ITOS series and ESSA-8, make it possible not only to find dust storms and to study their structure, but also to trace their evolution. For example, TV pictures received from the American satellites ITOS-1 and ESSA-8 by the L.S.U. receiving station have been used to trace the origin and development of a dust storm over the African coast, and the subsequent movement of dust material over the Mediterranean Sea. The TV picture of the northern African coast from the ITOS-1 satellite at 3:00 p.m. on July 16, 1970 (see Figure 2a), recorded a dust storm whose center was located 300 km east of Tripoli. A bright spot (see Figures 2a, 1) with diffuse boundaries — the area of the storm — is easily visible in this region, along with the "tongue" of the dust cloud, also with diffuse boundaries, which extends over the surface of the water (see Figures 2a, 2) and gradually disappears at a distance of 180 km from the shore.

The heavy cumulus and cumulonimbus cloudiness in the vicinity of Tripoli takes the form of a bright band with torn and blurred edges. This cloudiness extends in a direction perpendicular to the shoreline over the Jebel Nefusa Plateau (see Figures 2a, 3). Over the Mediterranean Sea, the cloudiness continues in the form of two bands (cirrus clouds) that are less bright in tone, and also have blurred boundaries, at a distance of 300 km from the shore.

Analysis of the synoptic situation has shown that on July 15, 1970, a cyclone (whose center was located at 32° N. lat., and 8° E. long.) formed south of the Atlas Mountains in the region of the sand mass of the Great Eastern Erg Desert, on a diffuse cold front connected with a cyclone located over Western Europe. By 3:00 p.m. on July 16, this cyclone had filled up, and its center had moved southeastward (its new location was 30° N. lat., and 14° E. long.).

A dust storm originated on the northeastern periphery of the cyclone in front of the cumulonimbus cloud mass located over the Jebel Nefusa Plateau and connected with an occlusion front, at the point where the cooler northwesterly current and the dry and hot southerly current met.

The center of the origin of the dust storm was located in the accumulative boundary coastal lowland formed by sea and alluvial deposits. Extensive development of alluvial-proluvial deposits is a typical feature of the local region, in contrast to the entire belt of the coastal lowland. The northern edge of the Al Jebel al Garb Plateau is cut by numerous large wadis (dry valleys), in the mouths of which are located cones from the discharge of intermittent watercourses; these cones flow together on the coastal plain. The friable proluvial deposits (from the intermittent watercourses) are full of dust particles. Salt marshes, whose salt deposits may serve as a source of dust during the dry period of the year, are widespread in the locality under examination. Moreover, the surface deposits are poorly concealed by the plant cover of the steppes that are developed here and that have turned into deserts. Under conditions in which the soil is poorly secured by the vegetation, during periods of intensive winds, dust particles are blown from the soil and dust storms similar to the one recorded in the TV picture originate. /22

The masses of dust raised from the ground by strong vertical streams in the area of the front (the wall of the storm) were picked up by the southerly current. The sharper southern boundary of the center of the storm, which is curved along the front, is easily visible in the picture. The dust cloud that had formed extended over the surface of the Mediterranean Sea.

At 3:00 p.m. on July 16, the weather station at Misurata recorded the presence of dust raised into the air, with a horizontal visibility of 3.5 km.

In the TV picture received almost twenty-four hours later, at 11:00 a.m. on July 17, 1970, from the AES ESSA-8 (see Figure 2b, 4), we can see the dust cloud over the Mediterranean Sea in the form of a band (up to 80 km wide) that extends from Cyrenaica (Libya) to Greece, and that is considerably less bright than the cloudiness with diffuse boundaries. The dust moved with the southerly current at a speed of 36 kilometers per hour. By 3:00 p.m. on July 17, the band of dust in the TV picture had moved 100 km to the east. At 3:00 p.m. in southern Greece, the presence of dry haze was recorded, with a horizontal visibility of 8 km. The synoptic situation at that time was the following. The cyclone that had been located south of Tripoli had moved eastward and had filled up, but the low pressure trough that extended from the central regions of Europe through the Balkans to North Africa remained; the stable southerly current in front of the cold front also remained. According to the barometric pressure topographical maps, this current continued up to an altitude of 5 km.

Thus, with the aid of television pictures received from a meteorological satellite, it is possible not only to find a dust storm, but also to trace the sequence of its movement and development.

In addition, using pictures of the high-altitude dust cloud that appears as a result of a dust storm, it is possible to trace the path of the movement of the dust material, and to find the areas on which it might be deposited. In particular, as the data show, dust storms undergoing daily fluctuations (deviations from average /23
values) , with a maximum development time of 14 - 15 hours, develop and evolve along with medium scale meteorological phenomena. In the process of their evolution, dust storms pass through a number of stages — from a whirlwind at ground level to the formation of a dust cloud at high altitudes. TV pictures make it possible to estimate the speed at which the dust material is moved, the dimensions of the dust cloud and the length of time that it exists (in this case, during a 24-hour period). They also make it possible to analyze more correctly the synoptic situation in regions of which we do not have a thorough meteorological knowledge (deserts and areas of the sea). On the basis of the sharp boundary of a dust storm along the line of a front (the wall of the storm), it is possible to determine more precisely the position of the cold front near the Earth, and, on the basis of the boundary of high-altitude dust clouds, it is possible to determine more precisely the position of the front and the direction of the wind at high altitudes.

3.2. <u>The structure of dust storms</u>. Space pictures of the Earth provide an ideal basis for studying the structure of dust storms. Previously, very valuable but extremely scanty data could be obtained by means of aerial photography. However, aerial photographs record only the small elements of the structure of these formations — the medium scale structure of the individual parts of a dust storm. Thanks to their incomparably greater field of view, space pictures have made it possible for the first time to find out the features of the large scale structure of dust storms. The field of view in local photographs from MS is relatively small. In these pictures, the stream pattern of a local dust current is clearly visible in the form of striation (for example, in the photograph of northwestern Arabia; see Figure 9). There, the division of the dust current into streams is engendered by the heterogeneity of the surface relief — by the presence of monadnock elevations along its route. Local photographs are less suitable for studying the structure of large dust formations, since they depict only fragments of a dust storm that conceals to one extent or another the elements of the surface.

TV pictures, especially global space photographs of the Earth, record large and even gigantic dust-wind formations, and make it possible to study the large scale elements of their structure. For example, analysis of a TV picture over Mesopotamia (see Figure 4), received from an altitude of about 1400 km, showed [15] that the structure of the dust storm there consisted of four subparallel streams. The most powerful of them are marked by the brightest tones; they extend over a distance of about 600 km, and they are 25 - 40 km wide. The other streams, which are less powerful and less bright in tone, are also smaller in size: the westernmost stream is about 400 km long and about 20 km wide; the two eastern streams are about 500 km long, and 20 - 25 km wide.

Thus, interpretation of space pictures has made it possible to obtain not only data concerning the dimensions of the elements of the structure of dust-sand formations, but also characterizations of these formations in terms of their brightness in the pictures, which may indicate the degree of turbidity of the atmosphere when the turbid layer has a different density. In order to obtain this data, a TV picture of the same region taken at the same time of day, but without a storm, was chosen for each picture of a storm. Identical profiles were chosen for both pictures, such that they passed through areas with a previously known albedo in the area of the spectrum with a wavelength λ = 0.5 - 0.75 microns. In the case of Mesopotamia, the following areas were chosen: the sea (albedo 6 - 7%), stony desert (20 - 25%), sandy desert (30 - 35%), and heavy cumulus cloudiness (75 - 80%). For the chosen sections of the surface, microphotometer recordings were used to calculate the average values of the optical density of the negative picture, and then characterizations were drawn up for the curves of the dependence of the albedo on the density of the picture. The curves showed a rather high correlation between optical density (the density of the picture — densitometric data) and the albedo of the surface; therefore, use of optical densities as a criterion for classifying the natural entities proved to be reliable. /24

Densitometric analysis of the TV picture (of the dust current over Mesopotamia) made it possible to study in greater detail the structure of the surface. According to the degree to which the albedo of the Persian Gulf increased (that of the Gulf being the lowest and most constant, as compared to the other surfaces), four gradations of dust turbidity of the atmosphere were defined: mild — increasing the albedo by up to 9%; moderate — increasing the albedo by 9 - 12%; average — by 12 - 18%; and severe — by 18 - 25%. Only in the last case does dust turbidity completely conceal the surface; in the other cases, certain elements of the landscape show through the dust clouds, and can be seen in the picture. In the last case, the albedo of the dust was 25 - 30% (determined by means of the characterization of the curve). In the other cases, the albedo constitutes a system comprising the surface plus the dust layer.

Combined analysis of the TV picture (see Figure 4) and the data from microphotometer recordings made it possible to construct a spatial picture of the distribution among the four gradations of the dust turbidity in the region encompassed by the storm (Figure 10). Using data from analysis of TV pictures, it was possible to trace the smaller-scale structure of the storm's dust streams in this region from the Soviet meteorological satellite Kosmos-226 (see Figure 5).

Using the method that has been described, a microphotometric analysis of this negative picture has also been done.

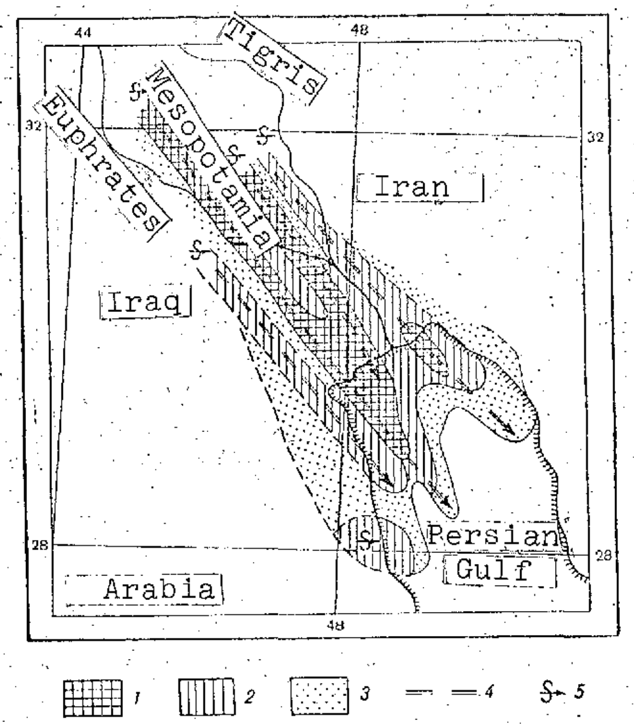

Figure 10. Map-diagram interpreting the dust storm over Mesopotamia on the basis of a TV picture from the ITOS-1 meteorological satellite taken on July 17, 1970 (see Figure 4):

1 — severe dust turbidity; 2 — average turbidity; 3 — moderate turbidity; 4 — the direction of the dust currents; 5 — the dust storms

The microphotometric profile (Figure 11) intersects two of the three large dust bands that are visually distinguishable in Figure 5a. Both large scale structures of the dust cloud are distinguished on the profile by two peaks: the maximum values of optical density, defined by the maximum values of their albedo (55 - 60%). Relatively smaller elements of the structure of the dust current — three small streams between the two aformentioned large ones — are also differentiated on the basis of the characterizations density of the picture. In addition, another, smaller dust /25 stream may be distinguished within the second large northern one. The effect of the underlying surface on the density of the picture of the dust current is clearly visible when comparing the two microphotometric profiles (Figure 11) made from different sequential TV pictures — with the storm and without it. Thus, for example, the power of the dust current undoubtedly decreases over the valley of the Euphrates River, which has an abundant and thick plant cover and over which only dust from other regions passes; the albedo of the dust layer also drops sharply — 37 - 44%.

By analyzing the profiles together with the picture (see Figure 5), it is possible to conclude that the sections of the streams with the highest albedo, equal to 55 - 60%, are located over regions in which soils that are easily blown away are widely developed; these soils are the largest sources for replenishing the wind currents with dust material.

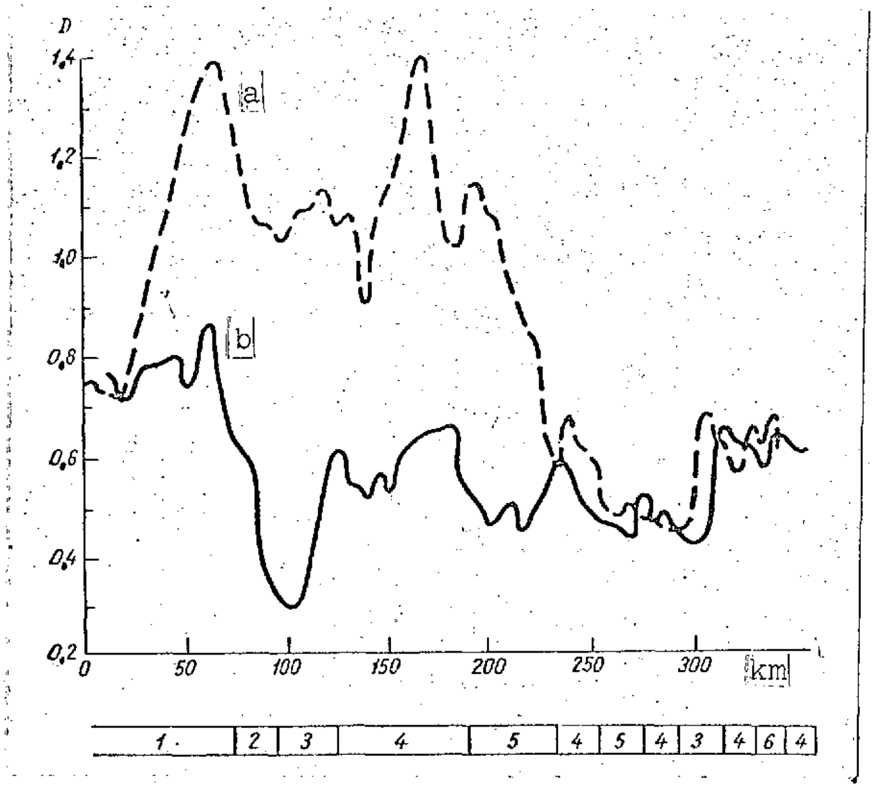

Figure 11. Microphotometric profiles of the TV pictures of Mesopatamia with a storm (a) on the basis of Figure 5a, and without a storm (b):

Elements of the structure of the underlying surface: 1 — the poorly secured sand mass of Er Rakhad; 2 — elevated watershed plain; 3 — valleys with thick plant cover; 4 — flat accumulative lowland plain composed primarily of loam deposits; 5 — relative depressions in a lowland plain with a somewhat more dense plant cover /26

The dust streams in the TV picture from the AES Kosmos-226 (see Figure 5) are marked by a higher albedo and sharper boundaries than the dust streams in the picture from the AES ITOS-1 (see Figure 4). This is perhaps connected with a difference in the condition of the atmosphere at the time the pictures were taken (degree of stability of the atmosphere, different wind profile in the layer of the atmosphere closest to the Earth).

Microphotometric analysis of a TV picture of the storm in the Lower Volga Region did not make it possible to distinguish bench mark surfaces with a known albedo and to construct a characteristic curve; therefore, the albedo of the dust was not estimated, and the spatial picture of the spread of the dust turbidity in the atmosphere was viewed in terms of the change in the density of the picture (Figure 12). This criterion made it possible to distinguish two areas of dust turbidity. The first is an area of severe turbidity, where the optical density of the picture increases by 0.2 - 0.35 (visibility decreases to 4 km), and the surface cannot be seen at all. In the second area, the optical density increases by 0.1 - 0.2 (visibility decreases to 7 km), and the surface may be seen. A comparison was also made between the change in the optical density of the TV picture because of the dust cloud and the change in the optical thickness of the atmosphere τ_0, using actinometric data from the Volgograd weather station. The increase in τ_0 from 0.26 (absence of dust) to 0.48 (infiltration of dust) corresponded to an increase of 0.25 in the optical density of the picture.

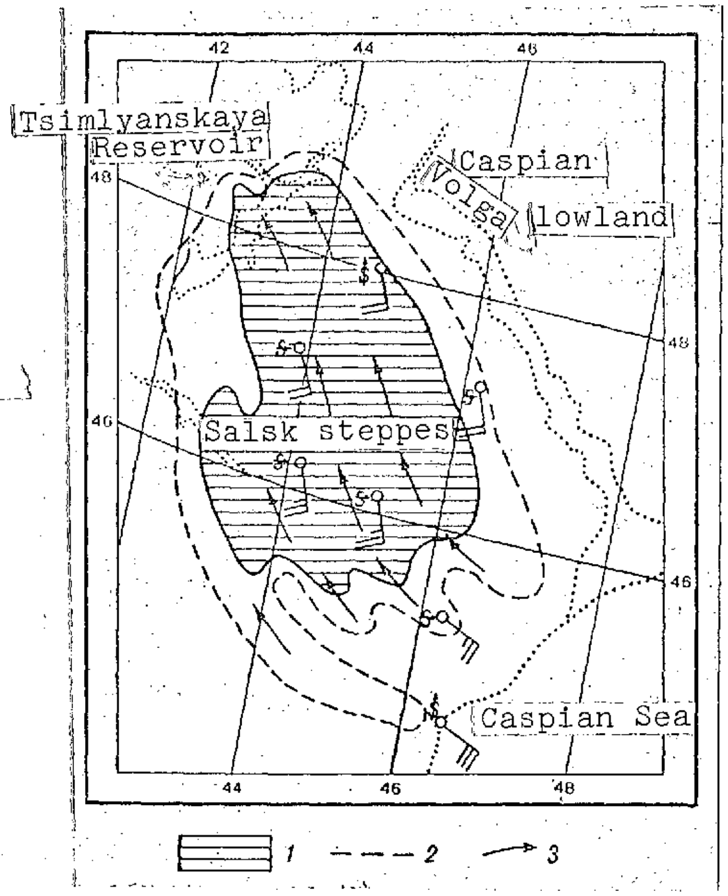

Figure 12. Map-diagram interpreting a dust storm in the Lower Volga Region according to TV pictures from the meteorological satellite Meteor-4, taken on June 13, 1970:

1 — severe turbidity (visibility 4 km); 2 — moderate turbidity (visibility 7 - 10 km); 3 — direction of the wind currents

/27

CONCLUSION

The study of the material dealing with large scale contaminations of the atmosphere obtained with the aid of space pictures has made it possible to bring to light the three most important directions in the study of this phenomenon: /28

1. The study of dust storms as a meteorological phenomenon: the conditions of their formation, their connection with various types of underlying surface and forms of large scale relief, the dynamics and structure of the phenomenon, frequency, etc.

The systematic analysis of space pictures makes it possible to obtain the most comprehensive conception of the spread of dust clouds. The opportunity to obtain space pictures regularly, above all, TV pictures from meteorological AES, opens up good prospects for studying the dynamics and structure of this phenomenon.

A study of dust storms' connection with the meteorological situation and with the nature of the underlying surface makes it possible to produce more successful forecasts of the storms, which might make it possible in the future to prevent this economically unfavorable phenomenon.

The use of dust clouds as indicators of air currents in the atmosphere will ensure a more comprehensive study of the nature of atmospheric circulation. Amassing statistical material concerning dust currents will bring to light the principal wind currents in arid and sub-arid zones, as well as their seasonal variations.

Space photography makes it possible to determine the dimensions of dust storms and to find out the composition of the dust (on the basis of data from studies of the centers in which the storms originate) and the concentration of the dust (on the basis of the nature of the turbidity). All this opens up good prospects for assessing the contribution of these natural contaminations to the thermal balance of the atmosphere.

2. The study of the formation and structure of aeolian relief as a function of the origin and development of dust storms, as well as the study of the different varieties of aeolian relief, their occurrence and their interrelationships. Desert relief is connected to a considerable extent with the action of dust storms. In particular, cellular and latticed sand appears in regions with poorly defined dust currents that change in direction, and large ridge sand with the ridges running in the same direction as the current, etc., appears in regions with well defined currents that have a constant direction. This line of research is possible only when combined use is made of both TV pictures of wind-dust currents and of MS photographs of a sufficiently high resolution, in which the various aeolian form are differentiated.

3. The study of the geological action of dust storms and confirmation of the conception of these storms [1] as a powerful geological agent (study of the movement of dust over great and very great distances and, in this connection, of the processes and areas of the deflation and accumulation of dust).

Analysis of the various types of space photographs, from global to local, in which the differentiation of the underlying surface is possible, makes it possible to localize more thoroughly the regions in which dust storms originate, and to study the dependence of their movement on the large scale relief and on the nature of the underlying surface, as well as to study the paths of their movement, the "unloading" regions, and their frequency. /29

Experience in the analysis of space pictures of dust storms and currents has shown that the satellites that can best be applied to the study of these phenomena are those whose orbits cross over the arid zones during the afternoon hours (local time), i.e., during the period of the maximum development of dust storms.

Analyses of the pictures have made it possible to note that for a more comprehensive study of the structure of this phenomenon, it is important to obtain simultaneous pictures of dust storms in two areas of the spectrum — in visible TV and in infrared. The infrared pictures should be comparable with the TV pictures with respect to spatial resolution.

Thus, there remains no doubt that even the small and by no means complete range of questions connected with the study from space of dust storms that has been examined in this pamphlet shows how promising is the application of space photography to the study of this phenomenon.

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